

# Angular dependence of resistivity in the superconducting state of $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$ single crystals

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**Abstract.** We report the results of angle dependent resistivity of  $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$  single crystals in the superconducting state. By doing the scaling of resistivity within the frame of the anisotropic Ginzburg-Landau theory, it is found that the angle dependent resistivity measured under different magnetic fields at a certain temperature can be collapsed onto one curve. As a scaling parameter, the anisotropy  $\Gamma$  can be determined for different temperatures. It is found that  $\Gamma(T)$  increases slowly with decreasing temperature, varying from  $\Gamma \simeq 5.48$  at  $T = 50$  K to  $\Gamma \simeq 6.24$  at  $T = 44$  K. This temperature dependence can be understood within the picture of multi-band superconductivity.

## 1. Introduction

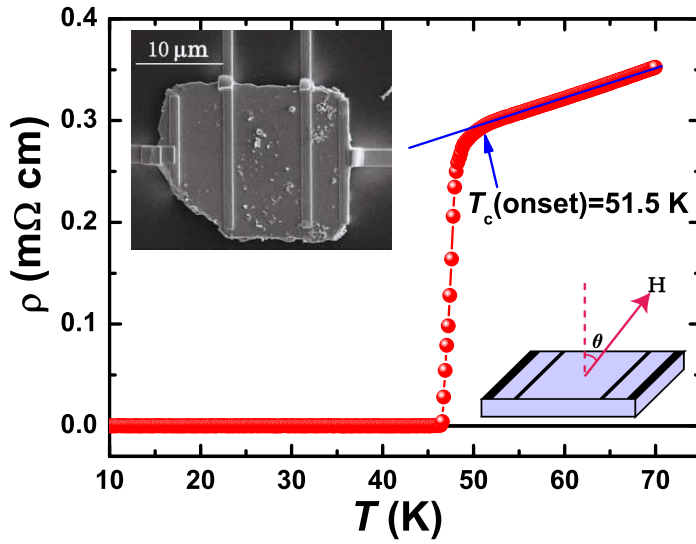
Since the discovery of superconductivity at 26 K in  $\text{LaFeAsO}_{1-x}\text{F}_x$  [1], great interests have been stimulated in the community of superconductivity. The superconducting transition temperature was quickly raised to about  $T_c = 55$  K in  $\text{SmFeAsO}_{0.9}\text{F}_{0.1}$  [2], and in other fluorine doped or oxygen deficiency samples. Moreover, hole-doped superconductors were also successfully synthesized in  $\text{La}_{1-x}\text{Sr}_x\text{FeAsO}$  [3] and  $\text{Ba}_{1-x}\text{K}_x(\text{FeAs})_2$  systems [4]. Many experiments have revealed that the iron-based superconductors belong to a family with unconventional pairing mechanism. These include the point contact tunneling spectroscopy [5, 6], NMR [7], specific heat [8], lower critical field [9] *etc.*. Meanwhile, so far many theoretical models have been proposed in order to have a basic understanding to the mechanism of superconductivity. As one of the basic parameters, the anisotropy  $\Gamma$  is crucial for both understanding the superconducting mechanism and its application, because it reflects directly the coupling strength between the "charge reservoir"  $\text{LnO}$  ( $\text{Ln} = \text{La}, \text{Ce}, \text{Pr}, \text{Nd}, \text{Gd}$  *etc.*) layers and the conducting  $\text{FeAs}$  layers.

An estimation of  $\Gamma \geq 30$  was made on  $(\text{Nd}, \text{Sm})\text{O}_{0.82}\text{F}_{0.18}\text{FeAs}$  polycrystals from the  $c$ -axis infrared plasma frequency [10]. Since the successful growth of  $(\text{Nd}, \text{Sm})\text{FeAsO}_{0.82}\text{F}_{0.18}$  single crystals [11, 12], precise determination of  $\Gamma$  was possible. The recent study on  $\text{SmFeAsO}_{0.8}\text{F}_{0.2}$  single crystals revealed that the magnetic anisotropy was temperature dependent, ranging from  $\Gamma \sim 8$  at  $T \simeq T_c$  to  $\Gamma \sim 23$  at  $T \simeq 0.4T_c$  [13]. Moreover, in our previous work on the  $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$  single crystals [14, 15],  $\Gamma$  was calculated from the upper critical fields parallel and perpendicular to the  $ab$ -plane, and was found below 5 near  $T_c$ . As a further study on the superconductivity of  $\text{NdFeAsO}_{1-x}\text{F}_x$  single crystals, here we report the angular dependence of resistivity in the superconducting state of  $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$  single crystals. By doing the scaling of the resistivity based on the anisotropic Ginzburg-Landau theory, the angle dependent resistivity measured under different magnetic fields at a certain temperature collapse onto one curve. Thus the anisotropy was determined for different temperatures.

## 2. Experiment

The single crystals of  $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$  were grown by flux method at ambient pressure, which have been described in Ref. [14, 12]. The typical lateral sizes of the crystals are about  $20 \mu\text{m}$  to  $70 \mu\text{m}$ , while thickness is about  $1 \sim 5$  micrometers. Electrical contacts were made using the Pt deposition technology of a Focused-Ion-Beam (FIB) system. The upper inset of Fig. 1 presents the image of the single crystal with Pt leads.

The angle-resolved resistivity measurements were carried out on a Physical Property Measurement System (PPMS, Quantum Design) with magnetic fields up to 9 T. The angle  $\theta$  was varied from  $-10^\circ$  to  $190^\circ$ , where  $\theta = 0^\circ$  corresponded to the configuration of  $H \parallel c$ -axis and  $\theta = 90^\circ$  to  $H \parallel ab$ -plane, respectively (as shown in the lower inset of Fig. 1). The veracity of the angle was ensured by the good  $c$ -axis orientation of the crystals, which have been demonstrated by the X-ray diffraction (XRD) analysis [12]. In our measurement,



**Figure 1.** (Color online) The resistive superconducting transition at zero magnetic field with  $T_c(\text{onset}) \approx 51.5\text{K}$  and  $\Delta T \approx 4\text{K}$ . The upper inset shows the Scanning Electron Microscope image of the  $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$  single crystal with Pt leads. The lower inset illustrates schematically the definition of angle  $\theta$ .

the current density was  $150\text{ A/cm}^2$  and the current was always perpendicular to the magnetic field. The sample exhibited a sharp resistive superconducting transition at  $T_c(\text{onset}) \approx 51.5\text{ K}$  with  $\Delta T_c \approx 4\text{ K}$ , the residual resistivity  $\rho(0\text{K}) = 0.13\text{ m}\Omega\text{cm}$  and  $RRR = \rho(400\text{K})/\rho(0\text{K}) = 6.5$  (shown in Fig. 1), demonstrating the good quality of the single crystal.

### 3. Results and Discussion

The insets in Fig. 2 and Fig. 3 present four sets of data for angular dependence of resistivity at temperatures of 44 K, 46 K, 48 K and 50 K. Taking the  $\rho(\theta)$  data at  $T = 44\text{ K}$  (the inset of Fig. 2(a)) as an example, all the curves show a dip-like structure with the minimum at  $\theta = 90^\circ$  and maximum at  $\theta = 0^\circ$  and  $180^\circ$ . The angular dependence of resistivity is not very steep, this suggests the moderate anisotropy of the  $\text{NdFeAsO}_{0.82}\text{F}_{0.18}$  single crystal.

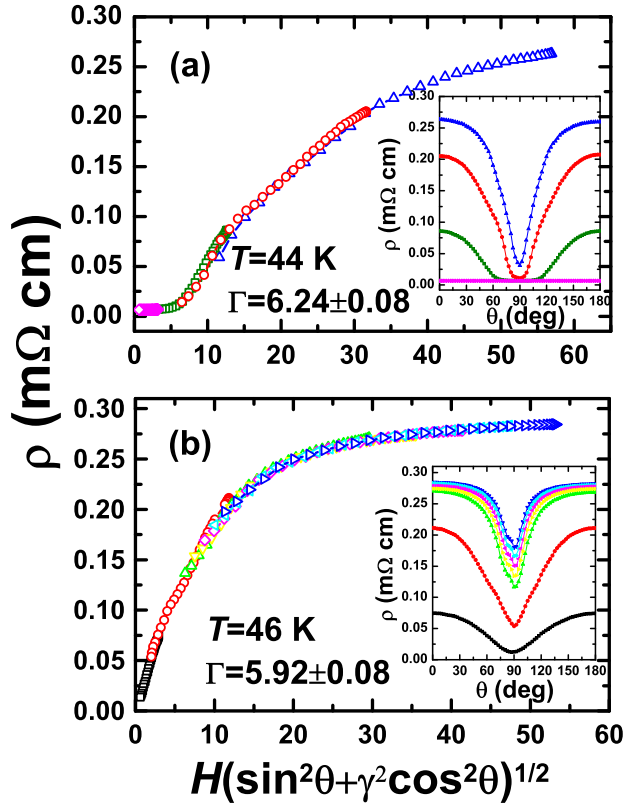
According to the anisotropic Ginzburg-Landau theory, the angular dependence of the upper critical fields is given by

$$H_{c2}^{GL}(\theta) = H_{c2}^{ab} / \sqrt{\sin^2(\theta) + \Gamma^2 \cos^2(\theta)}, \quad (1)$$

with

$$\Gamma = H_{c2}^{ab}(\theta = 90^\circ) / H_{c2}^c(\theta = 0^\circ) = (m_c / m_{ab})^{1/2} = \xi_{ab} / \xi_c, \quad (2)$$

where  $H_{c2}^{ab}$  and  $H_{c2}^c$  are the upper critical fields with  $H \parallel ab$ -plane and  $H \parallel c$ -axis,  $m_c$  and  $m_{ab}$  are the effective masses when the electrons move along  $c$ -axis and  $ab$ -plane respectively,

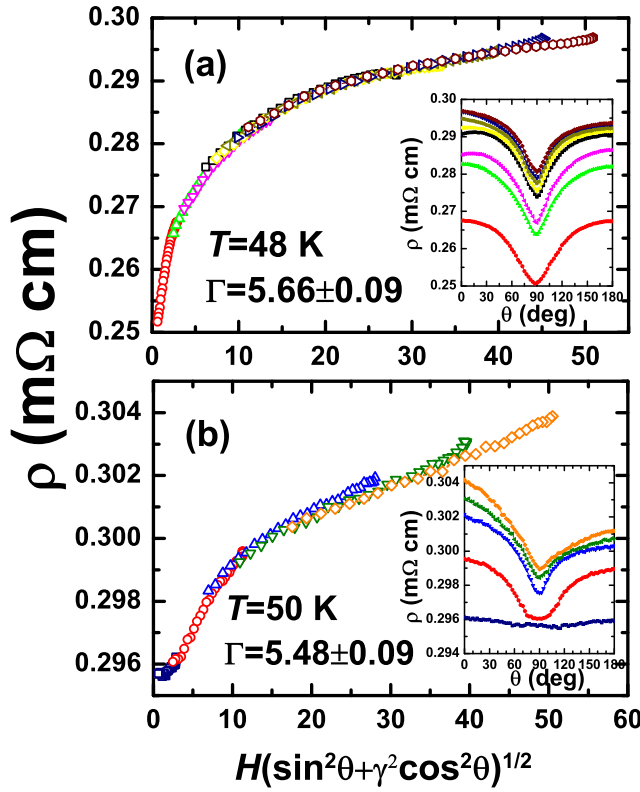


**Figure 2.** (Color online) Main panels: the resistivity as a function of  $\tilde{H}$  (see text) for (a)  $T = 44$  K and (b)  $T = 46$  K. Insets: the angular dependence of magnetoresistivity at (a)  $\mu_0 H = 0.5, 2, 5, 9$  T and (b)  $\mu_0 H = 0.5, 2, 5, 6, 7, 8, 9$  T. The anisotropy parameters are found to be  $6.24 \pm 0.09$  for  $T = 44$  K and  $5.92 \pm 0.09$  for  $T = 46$  K.

$\xi_c$  and  $\xi_{ab}$  are the coherence lengths along  $c$ -axis and  $ab$ -plane, respectively. On this basis, Blatter *et al.* developed a general scaling approach for the angular dependence of resistivity[16]. Based on this method, the resistivity measured under different magnetic fields at a certain temperature should collapse on one curve if  $x$ -coordinate is properly scaled. The rescaled function for  $x$ -coordinate is:

$$\tilde{H} = H \sqrt{\sin^2(\theta) + \Gamma^2 \cos^2(\theta)}, \quad (3)$$

By adjusting  $\Gamma$ , excellent scaling curves are obtained for each set of data at different temperatures, shown in the main panels of Fig. 2 and Fig. 3. In this treatment, only one variable  $\Gamma$  is employed as the fitting parameter, so the value of  $\Gamma$  is more reliable comparing with that determined from the ratio of  $H_{c2}^{ab}$  and  $H_{c2}^c$ , which might be affected by the criterion of  $H_{c2}$  determination. The anisotropy parameter  $\Gamma$  takes  $6.24 \pm 0.08$  for  $T = 44$  K,  $5.92 \pm 0.08$  for  $T = 46$  K,  $5.66 \pm 0.09$  for  $T = 48$  K and  $5.48 \pm 0.09$  for  $T = 50$  K. Such values are consistent with that we estimated from  $H_{c2}^{ab}/H_{c2}^c$ [14], but smaller than the values obtained on  $\text{SmFeAsO}_{0.8}\text{F}_{0.2}$  single crystals using a torque technique[13]. It is found that, as plotted in Fig. 4, the anisotropy increases slowly with decreasing temperature. The similar behavior of  $\Gamma(T)$



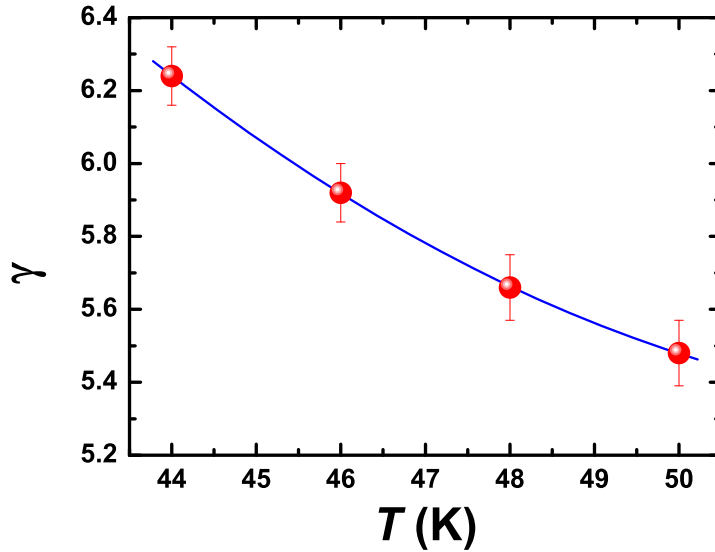
**Figure 3.** ((Color online)The resistivity versus  $\tilde{H}$  (see text) for (a)  $T = 48$  K and (b)  $T = 50$  K. The insets present the angular dependence of magnetoresistivity at (a)  $\mu_0 H = 0.5, 2, 3, 5, 6, 7, 8, 9$  T and (b)  $\mu_0 H = 0.5, 2, 5, 7, 9$  T. The scaling parameters are  $\Gamma = 5.48 \pm 0.08$  for  $T = 48$  K and  $\Gamma = 5.66 \pm 0.08$  for  $T = 50$  K

was also observed in SmFeAsO<sub>0.8</sub>F<sub>0.2</sub> single crystals[13], which was attributed to the two-gap scenario[17, 18]. In addition, it should be noted that the good scaling behavior suggests a field-independent anisotropy in our measuring range.

For comparison, in MgB<sub>2</sub>, a typical two-band superconductor, clear deviations have been observed between the experimental  $H_{c2}(\theta)$  and the anisotropy G-L description. Such a phenomenon was attributed to the different anisotropy factors of the two bands[19]. Whereas, no such deviation is found in our experiment, so we suggest that single band or multi-band with similar anisotropy parameters should exist in the NdFeAsO<sub>0.82</sub>F<sub>0.18</sub> superconductors.

#### 4. Summary

In conclusion, we have investigated the angle dependent resistivity in the superconducting state of NdFeAsO<sub>0.82</sub>F<sub>0.18</sub> single crystals. It is found that the  $\rho(\theta, H)$  data measured at a certain temperature can be described by a scaling law based on the anisotropic Ginzburg-Landau theory. Thus the values of anisotropy are extracted for different temperatures. It is



**Figure 4.** (Color online) Temperature dependence of anisotropy parameter  $\Gamma$ . The line is guided to eyes.

found that  $\Gamma(T)$  increases with decreasing temperature, which was attributed to the multi-band effect.

## 5. Acknowledgements

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*Angular dependence of resistivity in the superconducting state of NdFeAsO<sub>0.82</sub>F<sub>0.18</sub> single crystals* **7**

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